X-ray Optics needs for 3rd and 4th generation Light Source

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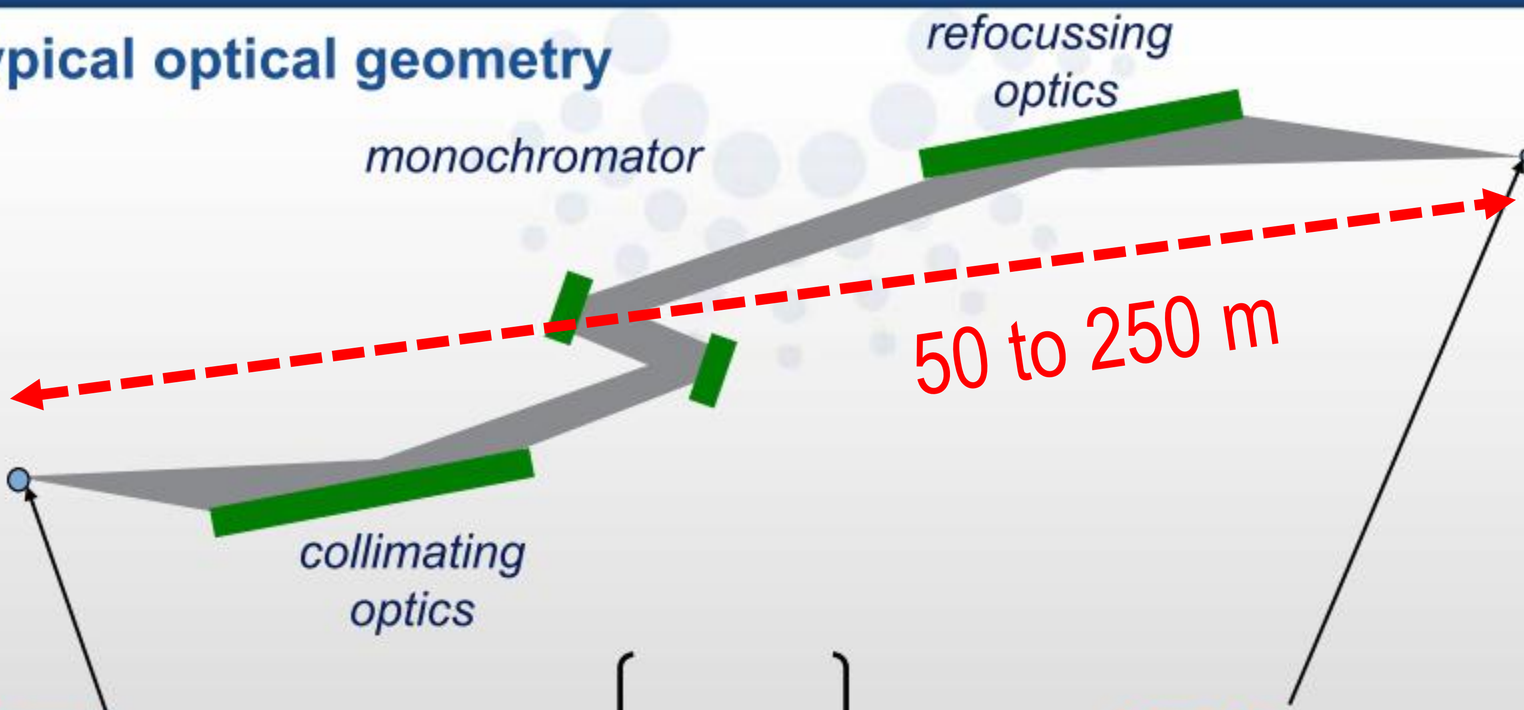
OUTLINE

- 3rd and 4th generation Light source

  NSLS II Example
- Optics needs
  - Diffractive – Refractive Lenses
  - Mirrors

BEAMLINES

Typical optical geometry



OPTICS

?

Source

- spectrum (ΔE/E)
- emittance (size x divergence)
- degree of spatial coherence
- brilliance (ph/s/mm^2/mrad^2/0.1%bw)
- polarisation (linear, circular, elliptic)

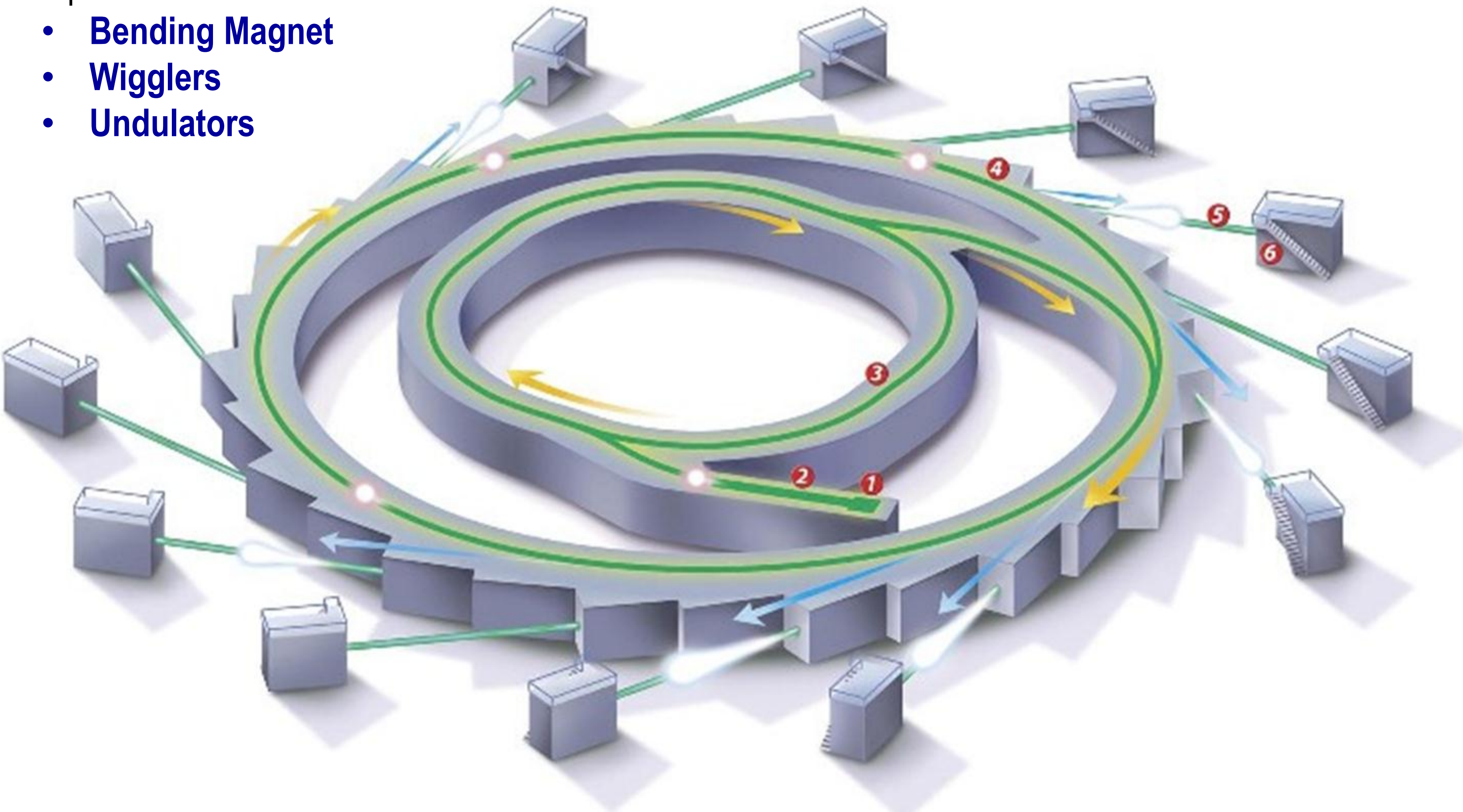
Sample

- beam size (μm)
- beam divergence (μrad)
- flux (ph/s)
- temporal coherence: ΔE/E
- spatial coherence
- polarisation

BEAMLINES

3 possible sources

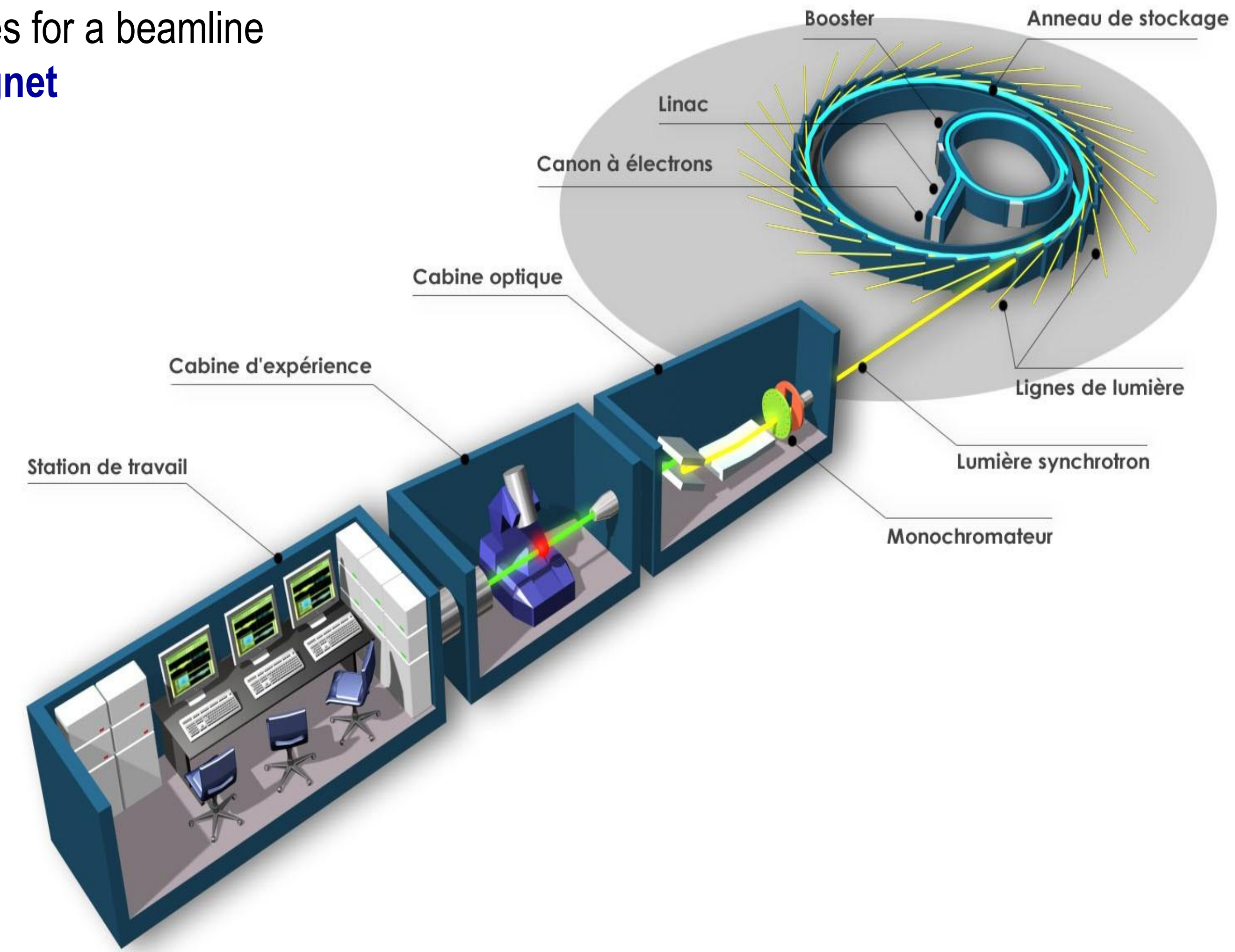
- **Bending Magnet**
- **Wigglers**
- **Undulators**



BEAMLINES

3 possible sources for a beamline

- **Bending Magnet**
- **Wigglers**
- **Undulators**



BEAMLINES

3 possibles sources **Bending Magnet – Wigglers - Undulators**

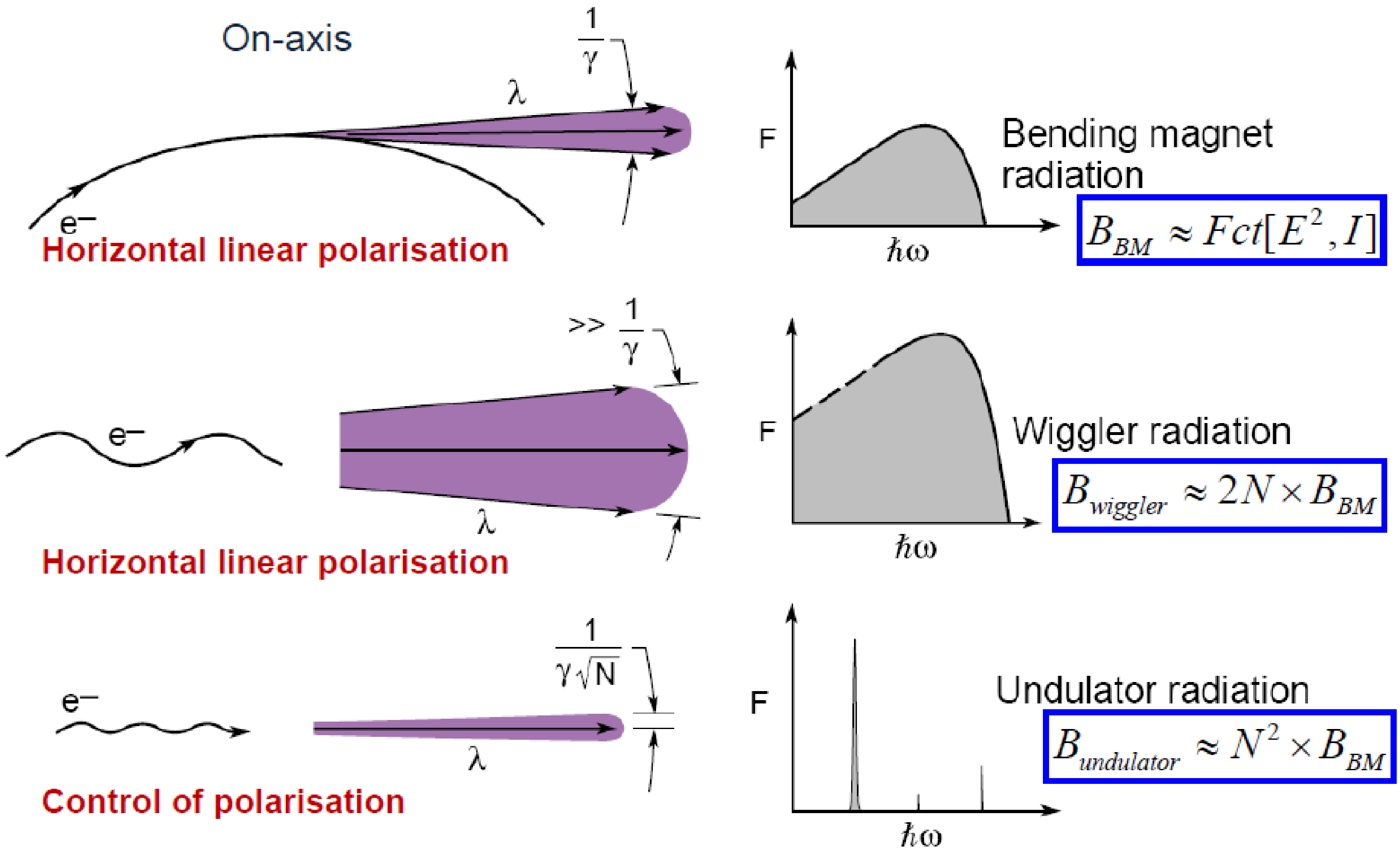
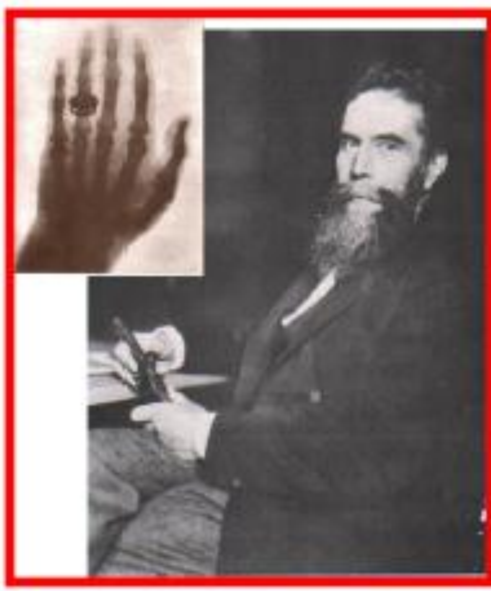
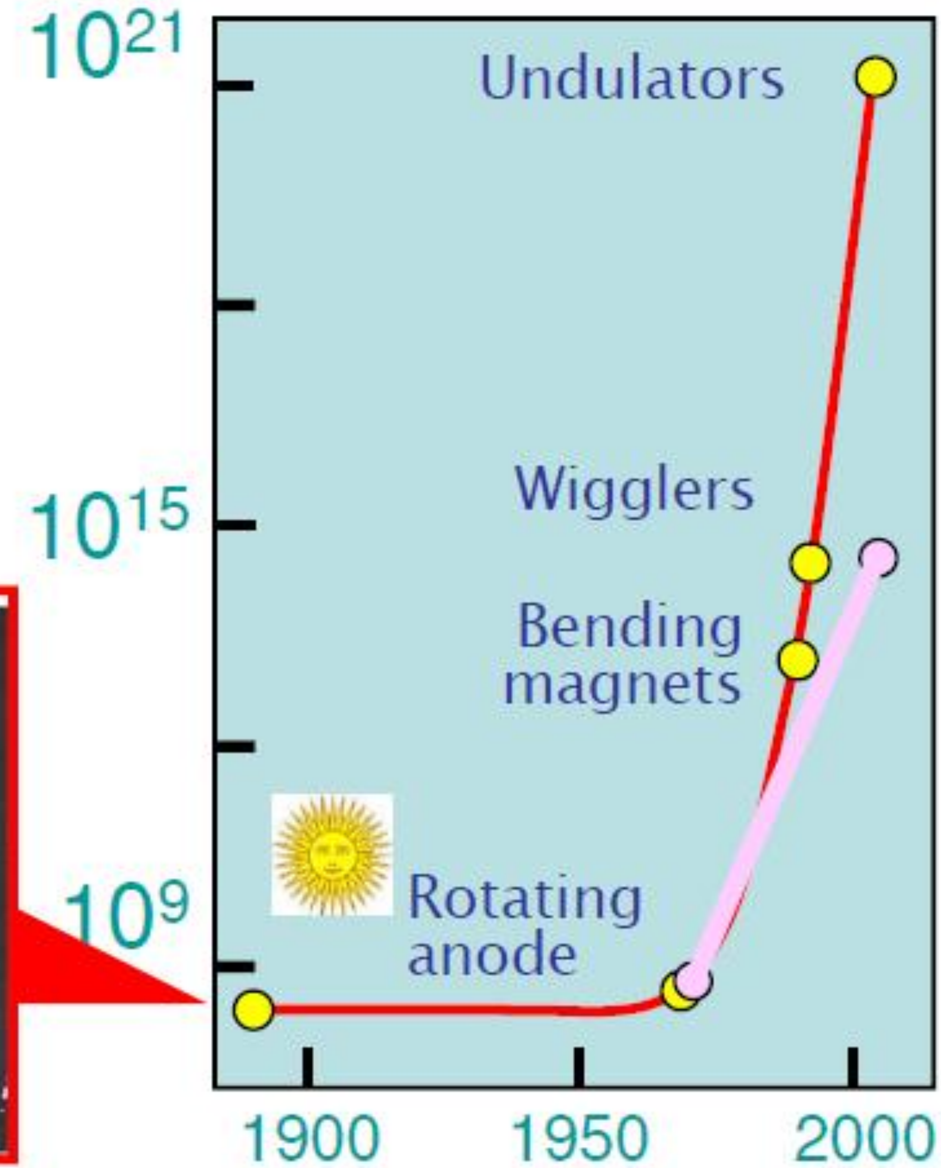


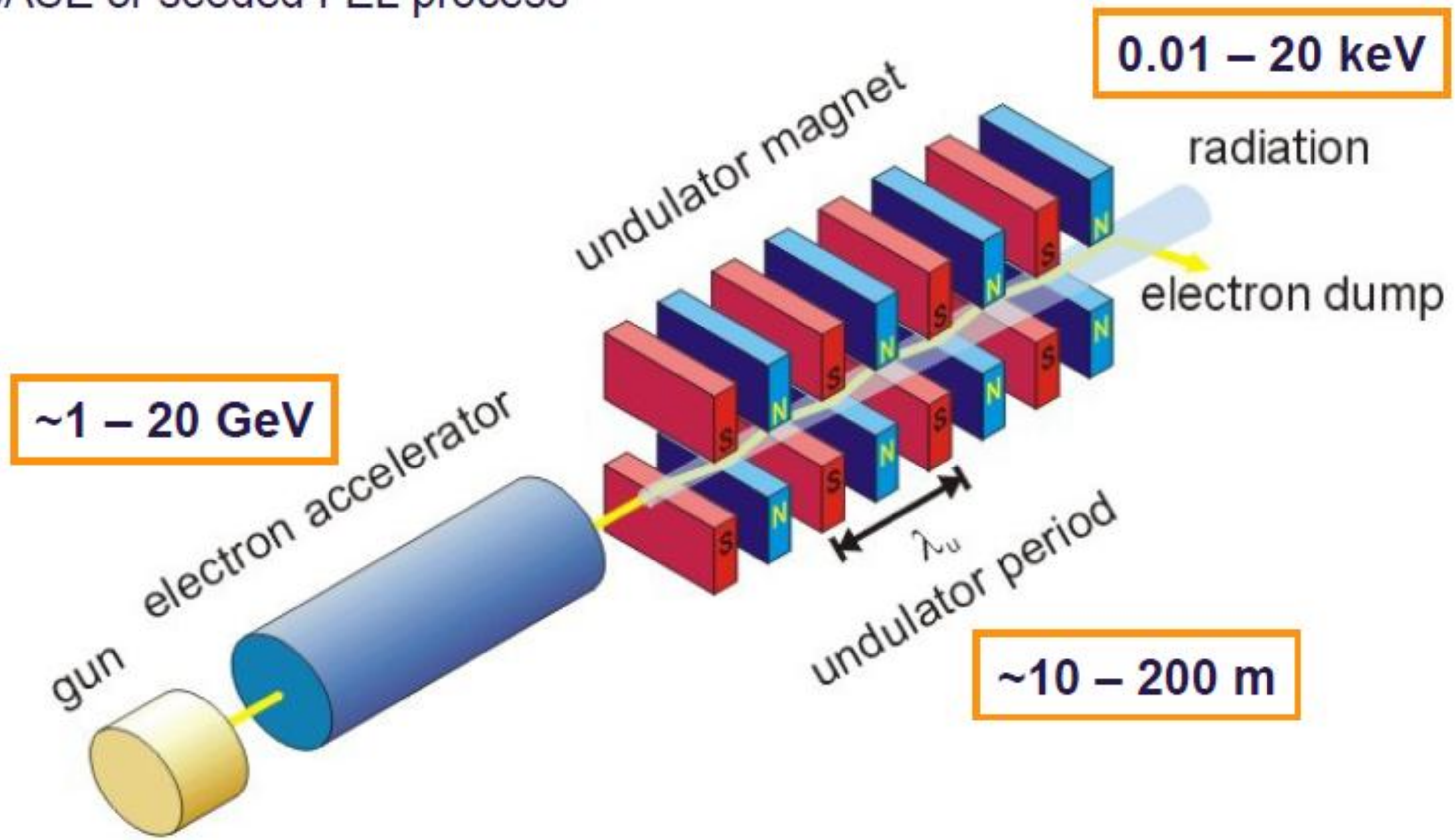
Figure of Merit : Brightness

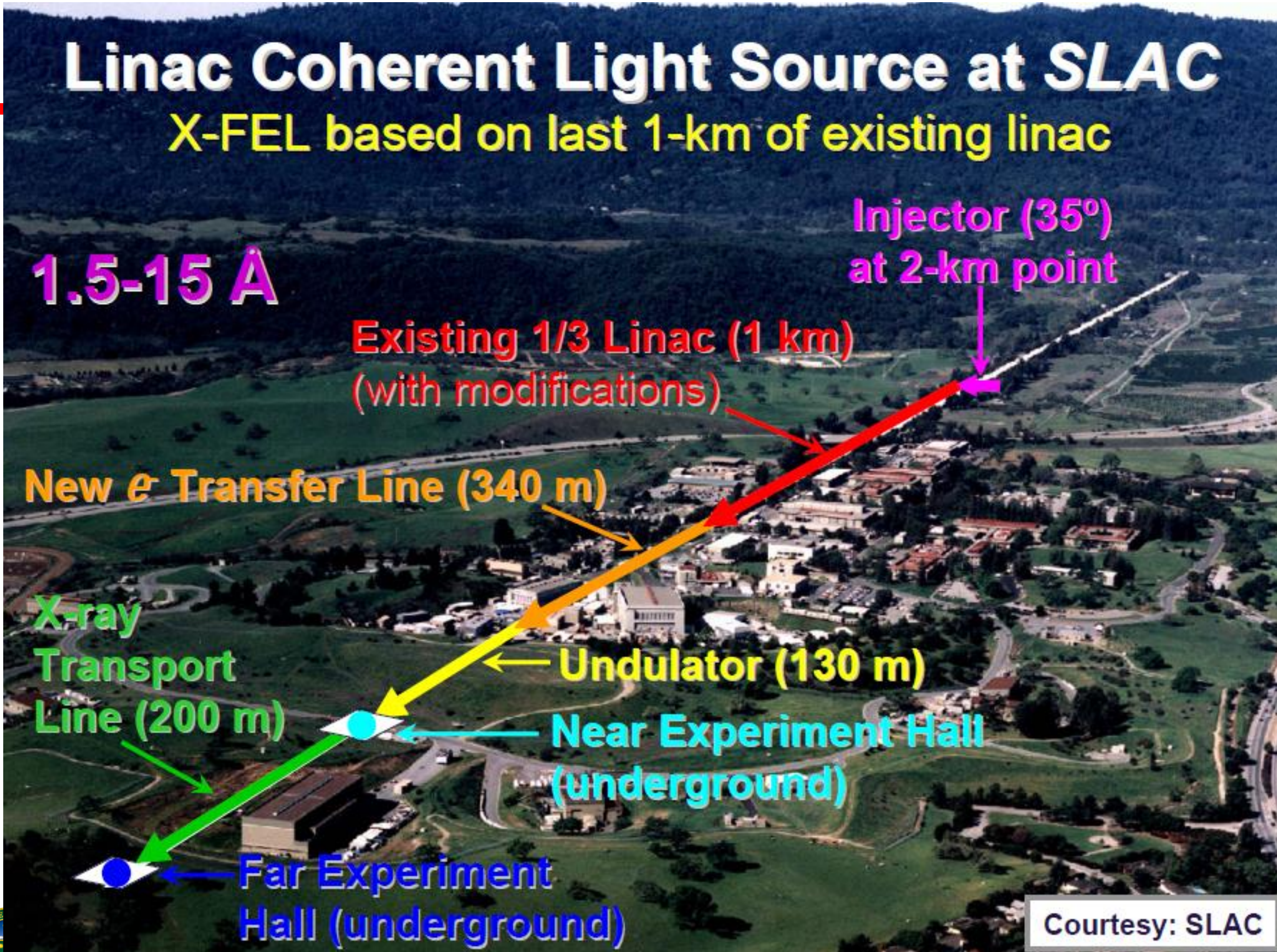




4^{th} generation source : undulators based

- low emittance high energy energy accelerator
- SASE or seeded FEL process




Linac Coherent Light Source at SLAC
X-FEL based on last 1-km of existing linac
Injector (35º) at 2-km point
1.5-15 Å
Existing 1/3 Linac (1 km) (with modifications)
New e⁻ Transfer Line (340 m)
X-ray Transport Line (200 m)
Undulator (130 m)
Near Experiment Hall (underground)
Far Experiment Hall (underground)
Courtesy: SLAC

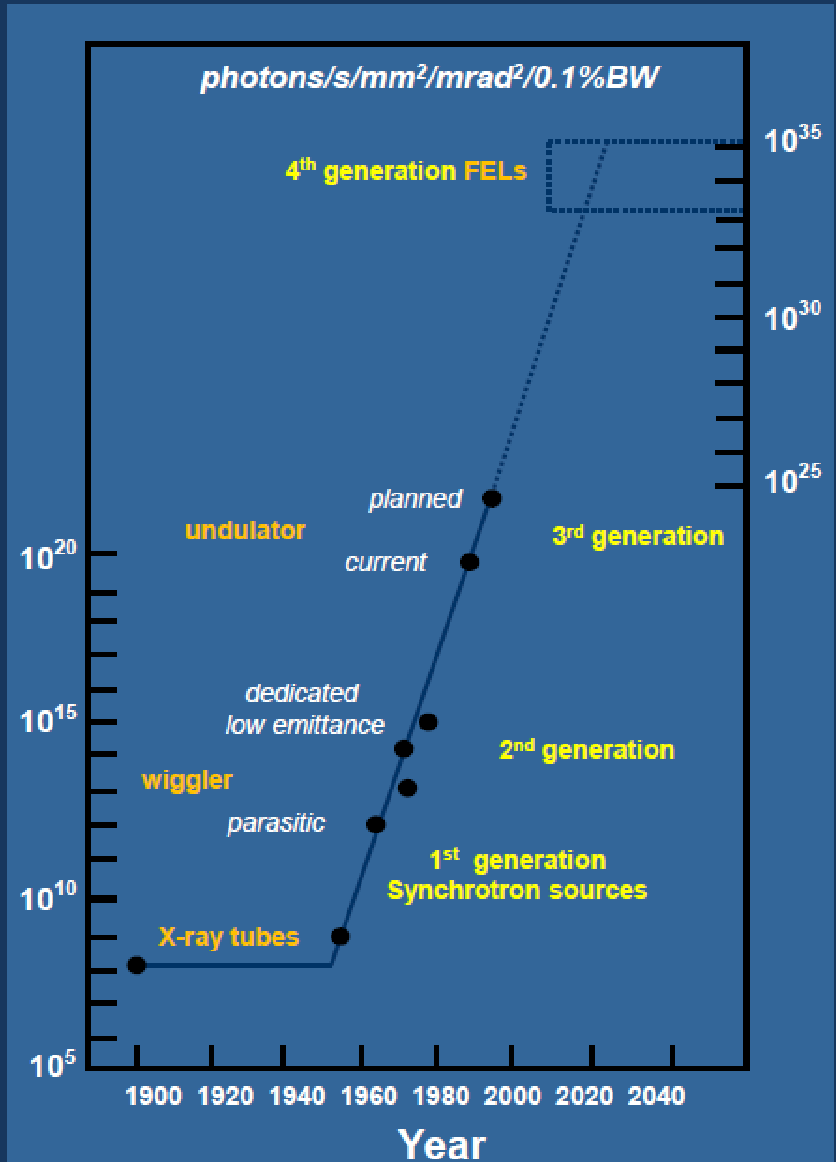
The figure of merit of the source: brilliance

Brilliance or *Brightness* *(flux density in phase space) is an invariant quantity in statistical mechanics, so that no optical technique can improve it.*

$$\text{Brightness} = \frac{\text{photon flux}}{(\Delta A)\,(\Delta \Omega)}$$

$$\text{Spectral Brightness} = \frac{\text{photon flux}}{(\Delta A)\,(\Delta \Omega)\,(\Delta\lambda/\lambda)}$$

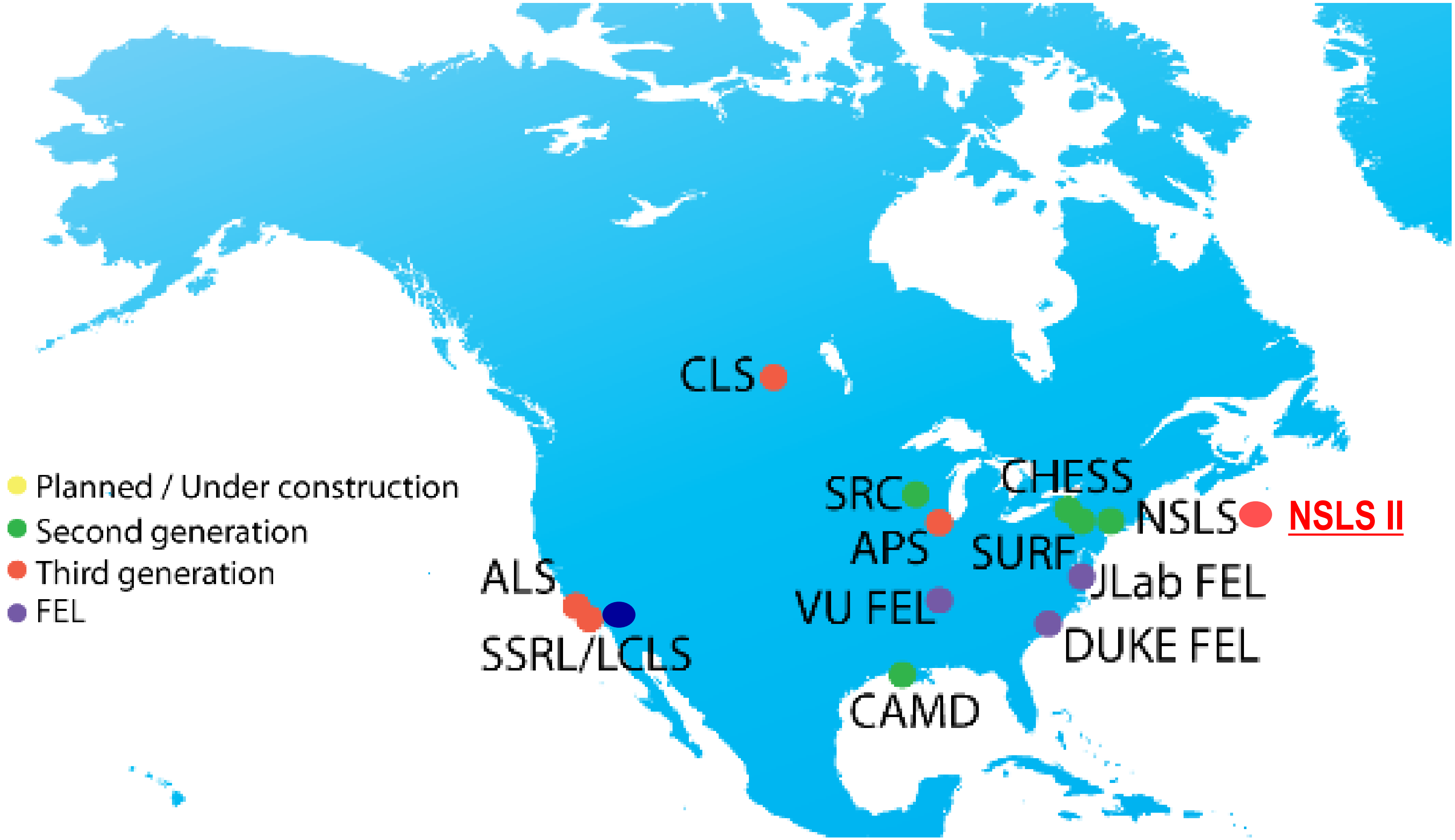
$$\frac{[\text{Photons/sec}]}{[\text{mm}]^2\,[\text{mrad}]^2\,[0.1\%\ \text{bandwidth}]}$$



3rd and 4th generation Light Source

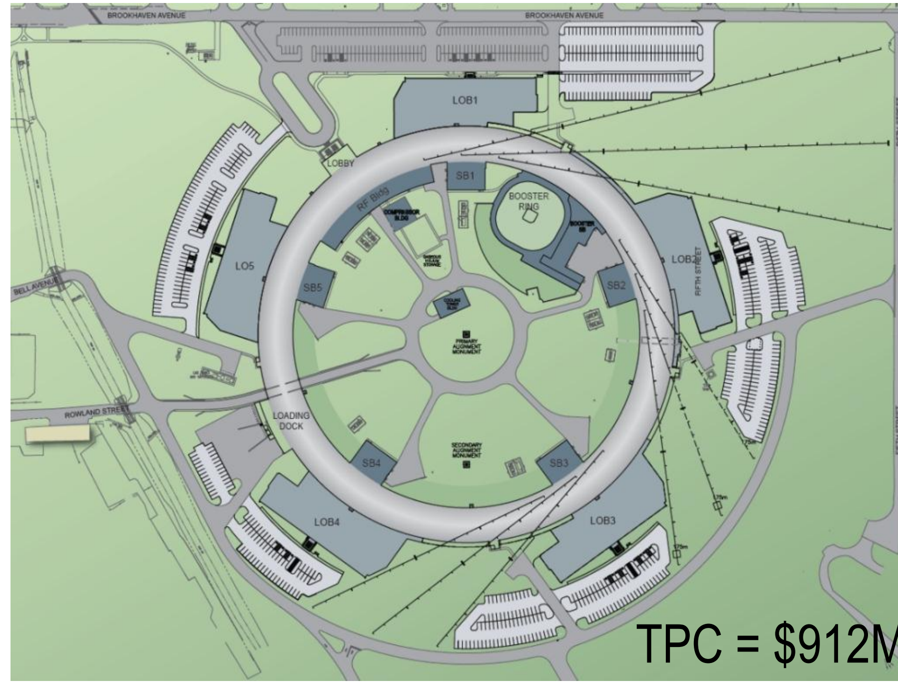
There are over 40 synchrotrons and fourth generation light sources around the world. The major light sources are shown below. For a full list, visit lightsources.org.

3rd and 4th generation Light Source



NSLS-II: Optimized 3rd Generation SR

- 3 GeV, 500 mA, Circumference 791 m
- Low emittance: **ε_x= 0.55, ε_y= 0.008 nm-rad**
- High brightness/flux from **soft to hard x-rays**
- Small beam size: σ_y= 2.6 μm, σ_x= 28 μm
- Pulse length (rms) ~15 psec
- **27 insertion device beamlines**
- **31 BM / 3PW / IR beamlines**
- Full built-out includes at least **58 beamlines, plus canted IDs**



High-β Straight Section (9.3m)

3-pole Wiggler Bending Magnet

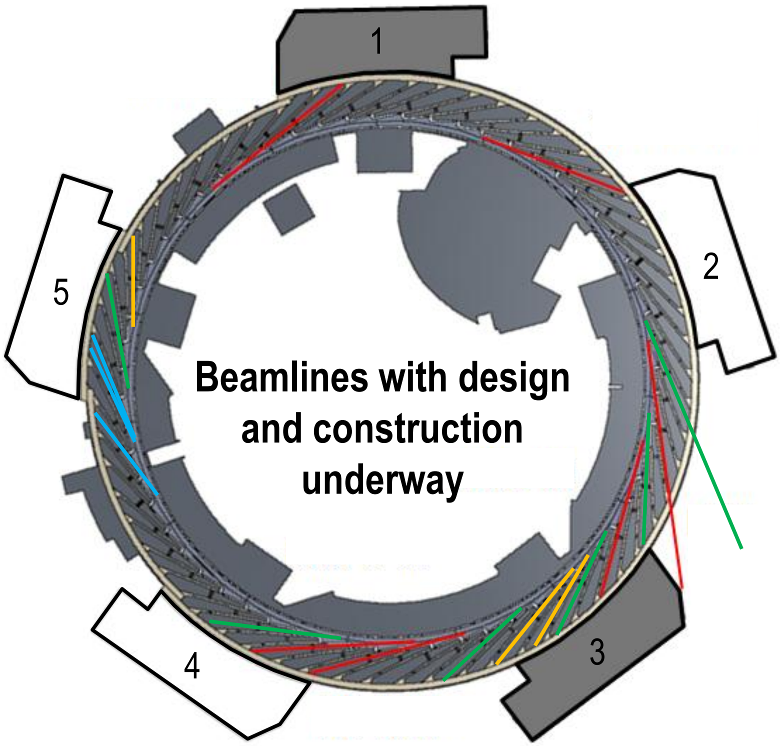
Low-β Straight Section (6.6m)

Key Project Milestones

Aug 2005	**CD-0**, Approve Mission Need	(Complete)
Jul 2007	**CD-1**, Approve Alternative Selection and Cost Range	(Complete)
Jan 2008	**CD-2**, Approve Performance Baseline	(Complete)
Jan 2009	**CD-3**, Approve Start of Construction	(Complete)
Feb 2009	Contract Award for Ring Building	(Complete)
Aug 2009	Contract Award for Storage Ring Magnets	(Complete)
May 2010	Contract Award for Booster System	(Complete)
Feb 2011	1st Pentant Ring Building Beneficial Occupancy	(Complete)
Feb 2011	Begin Accelerator Installation	(Complete)
Feb 2012	Beneficial Occupancy of Experimental Floor	(Complete)
Mar 2012	Start LINAC Commissioning	(Complete)
Jan 2013	Start Booster Commissioning	
Jul 2013	Start Storage Ring Commissioning	
Apr 2014	Projected Early Completion; Ring Available to Beamlines	
Jun 2014	Early Project Completion; Ring Available to Beamlines	
Jun 2015	**CD-4**, Approve Start of Operations	

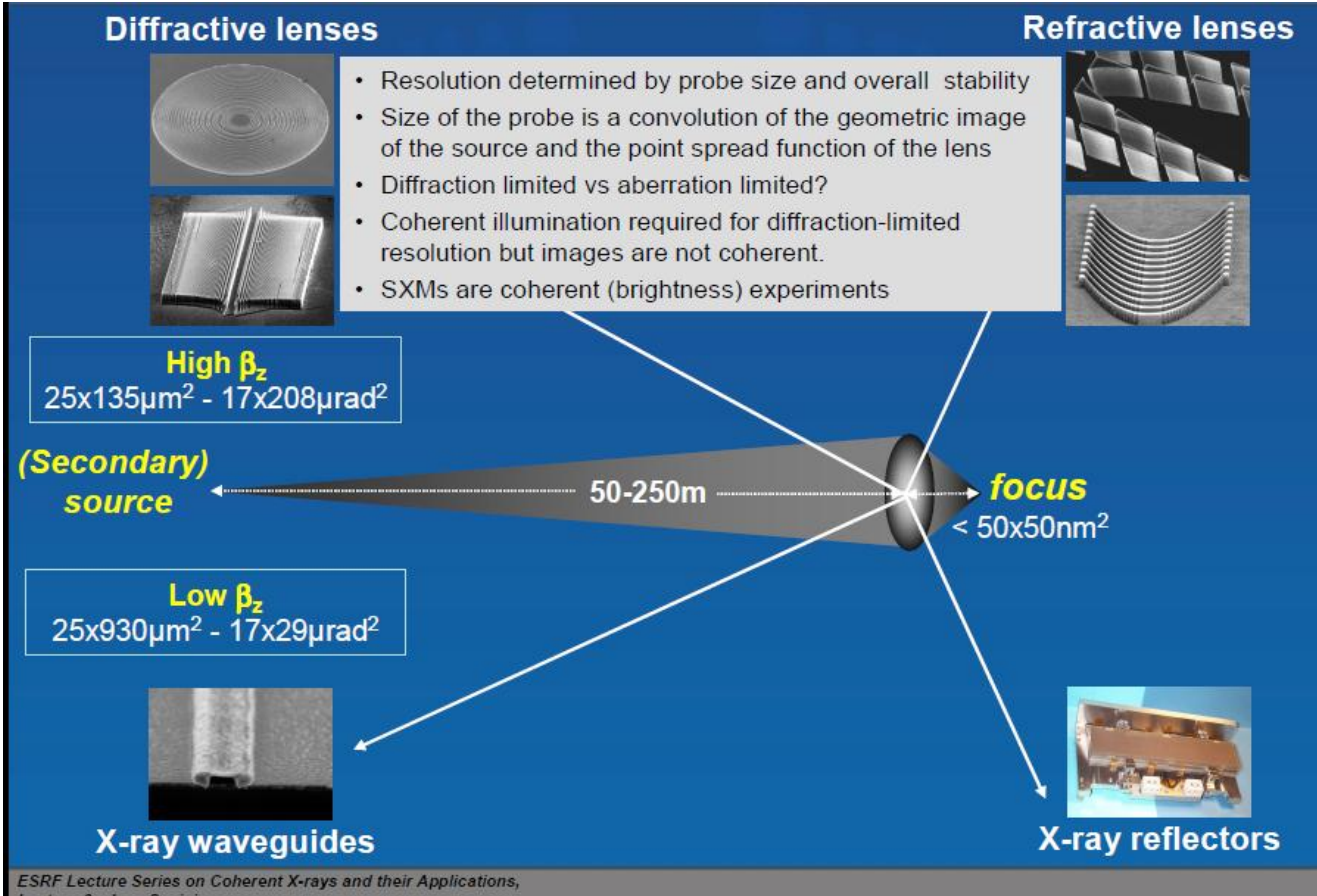
NSLS-II Beamlines Underway

18 Beamline Construction Projects Underway
21 Simultaneous Endstations (SE)
28 Total Endstations (TE)



22 additional beamlines (25 SE) have been proposed by the user community and approved by the SAC and NSLS-II but are not yet funded

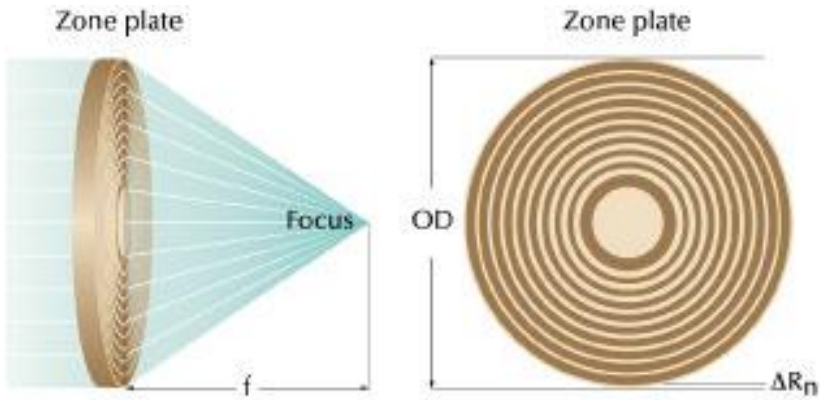
Beamline ConstructionProjects	SE	TE
NSLS-II Project Beamlines		
• Inelastic X-ray Scattering (IXS)	1	1
• Hard X-ray Nanoprobe (HXN)	1	1
• Coherent Hard X-ray Scattering (CHX)	1	1
• Coherent Soft X-ray Scat & Pol (CSX)	2	2
• Sub-micron Res X-ray Spec (SRX)	1	1
• X-ray Powder Diffraction (XPD)	1	1
NEXT MIE Beamlines		
• Photoemission-Microscopy Facility (ESM)	2	3
• Full-field X-ray Imaging (FXI)	1	1
• In-Situ & Resonant X-Ray Studies (ISR)	1	2
• Inner Shell Spectroscopy (ISS)	1	1
• Soft Inelastic X-ray Scattering (SIX)	1	1
• Soft Matter Interfaces (SMI)	1	2
NIH Beamlines		
• Frontier Macromolecular Cryst (FMX)	1	1
• Flexible Access Macromolecular Cryst (AMX)	1	1
• X-ray Scattering for Biology (LIX)	1	1
Type II Beamlines		
• Spectroscopy Soft and Tender (NIST)	2	6
• Beamline for Materials Measurements (NIST)	1	1
• Microdiffraction Beamline (NYSBC)	1	1
TOTAL	**21**	**28**

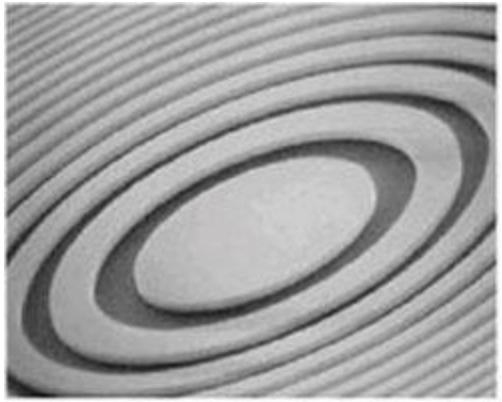

Diffractive lenses
Refractive lenses
• Resolution determined by probe size and overall stability
• Size of the probe is a convolution of the geometric image of the source and the point spread function of the lens
• Diffraction limited vs aberration limited?
• Coherent illumination required for diffraction-limited resolution but images are not coherent.
• SXMs are coherent (brightness) experiments
High β_z
25x135μm^2 - 17x208μrad^2
(Secondary) source
50-250m
focus
< 50x50nm^2
Low β_z
25x930μm^2 - 17x29μrad^2
X-ray waveguides
X-ray reflectors
ESRF Lecture Series on Coherent X-rays and their Applications, Lecture 6 - Jean Susini

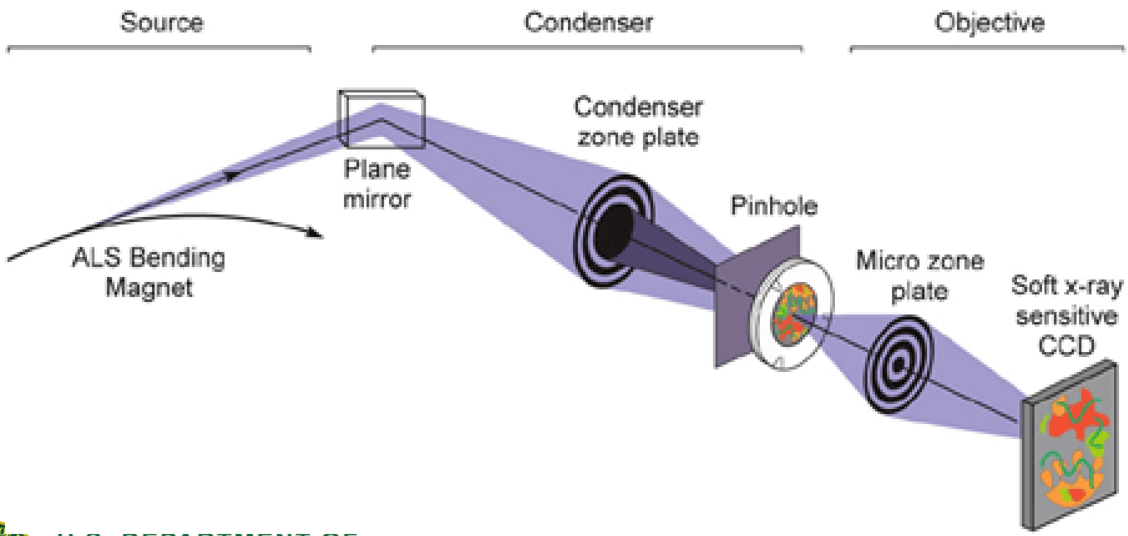
Diffractive – Refractive Lenses

Diffractive – Refractive Lenses

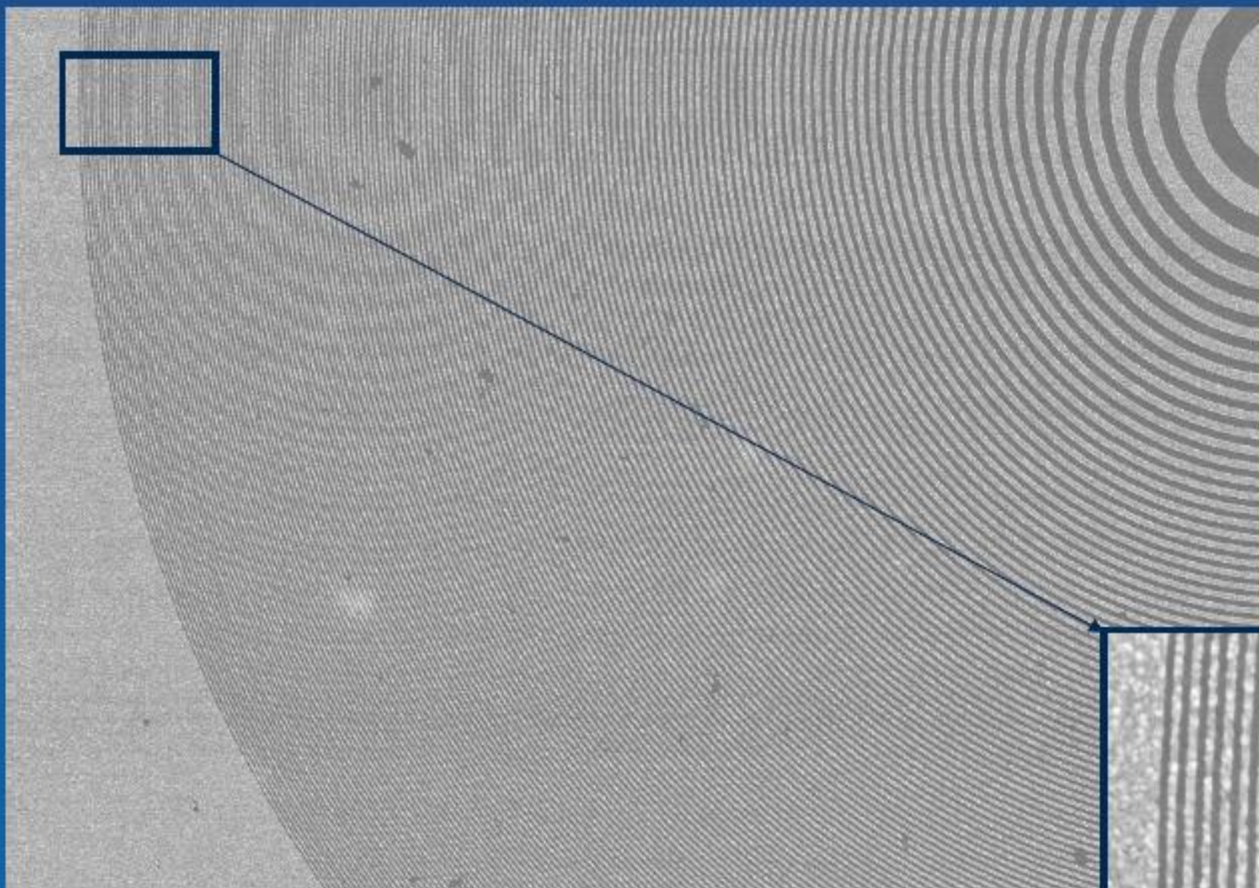
Zone plates are circular diffraction gratings with radially increasing line density.



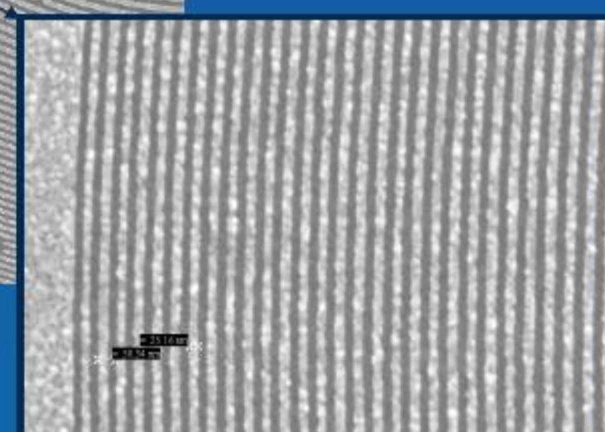




Diffractive Lenses



- Δr_N = 25 nm
- D = 63 µm
- N = 618 zones
- f = 650 µm
- NA = 0.05
  @ λ = 2.4 nm

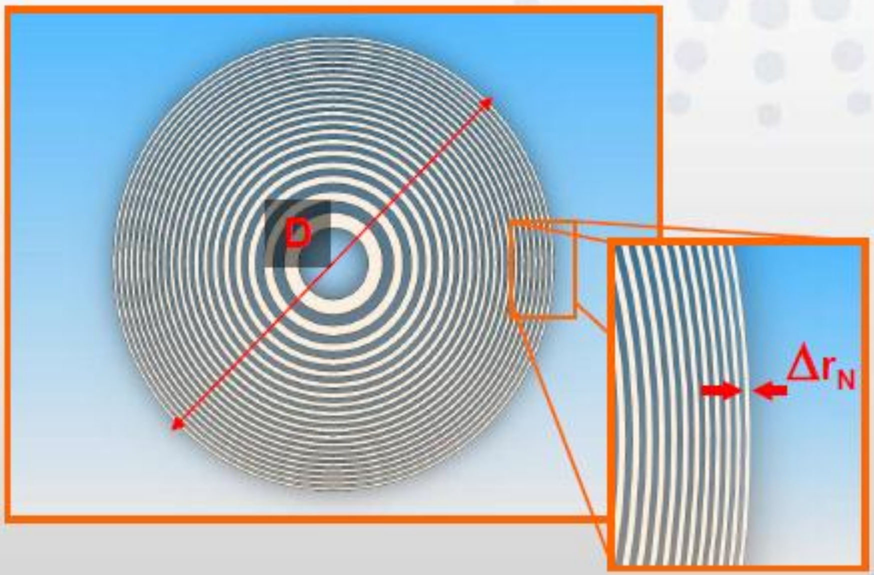


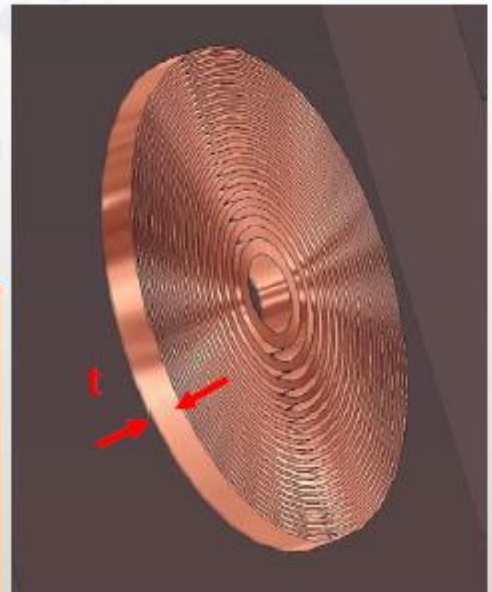
- **Δr_N = 15 nm**
  W. Chao *et al.*, *Nature* 435 (2005)

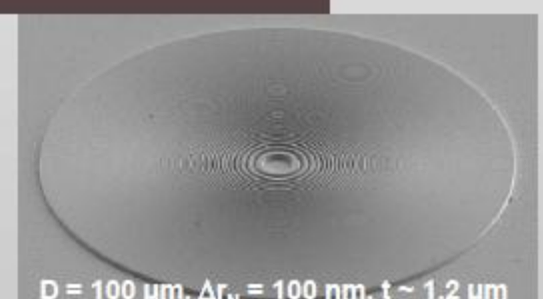
E. Anderson, *Center for X-Ray Optics*, LBNL, USA

Diffractive – Refractive Lenses

- **Diffractive X-ray Lenses: Circular transmissive diffraction gratings with radially decreasing line width giving focusing effect**



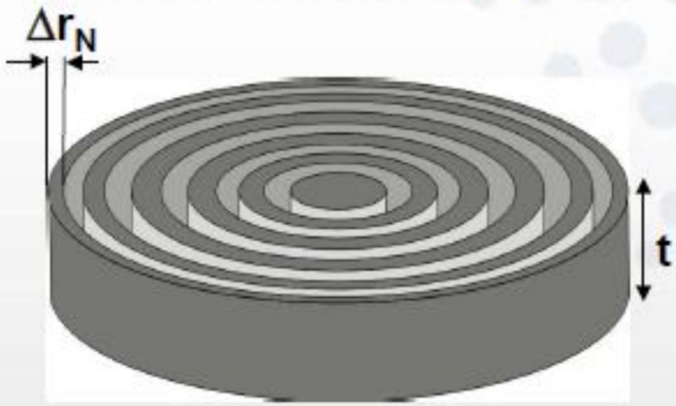




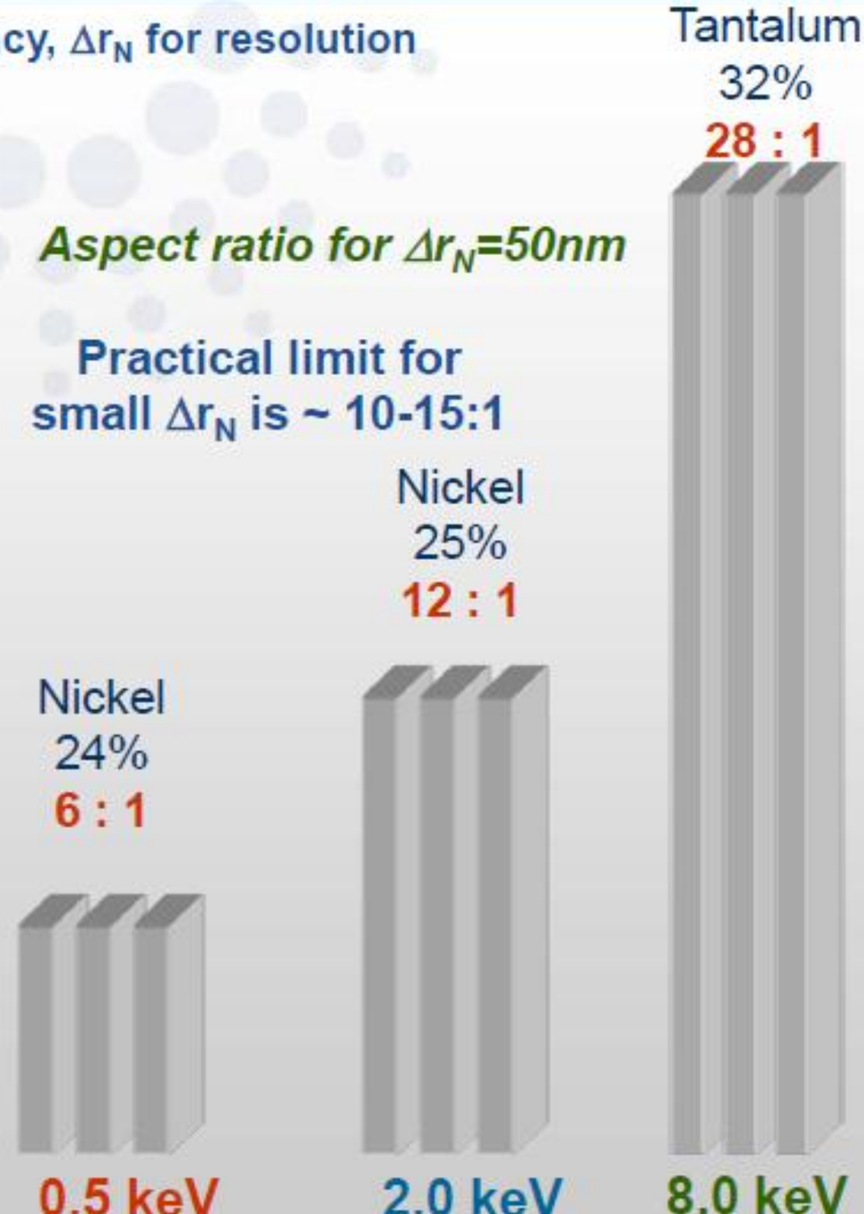
Alternate 'zones' modify phase/amplitude of incident wavefront: for material of thickness, t, wavelength, λ, refractive index $1-\delta-i\beta$, phase shift, $\Delta\phi$, is:

$$\Delta\phi = \frac{2\pi\delta t}{\lambda}$$

structure height, t, critical for efficiency, Δr_N for resolution



Material	t (μm)	ε (%)
E=0.5keV		
Ge	0.28	16
Ni	0.25	24
E=2.0keV		
Ni	0.60	25
Au	0.45	24
E=8.0keV		
Ta	1.70	32
W	1.50	33

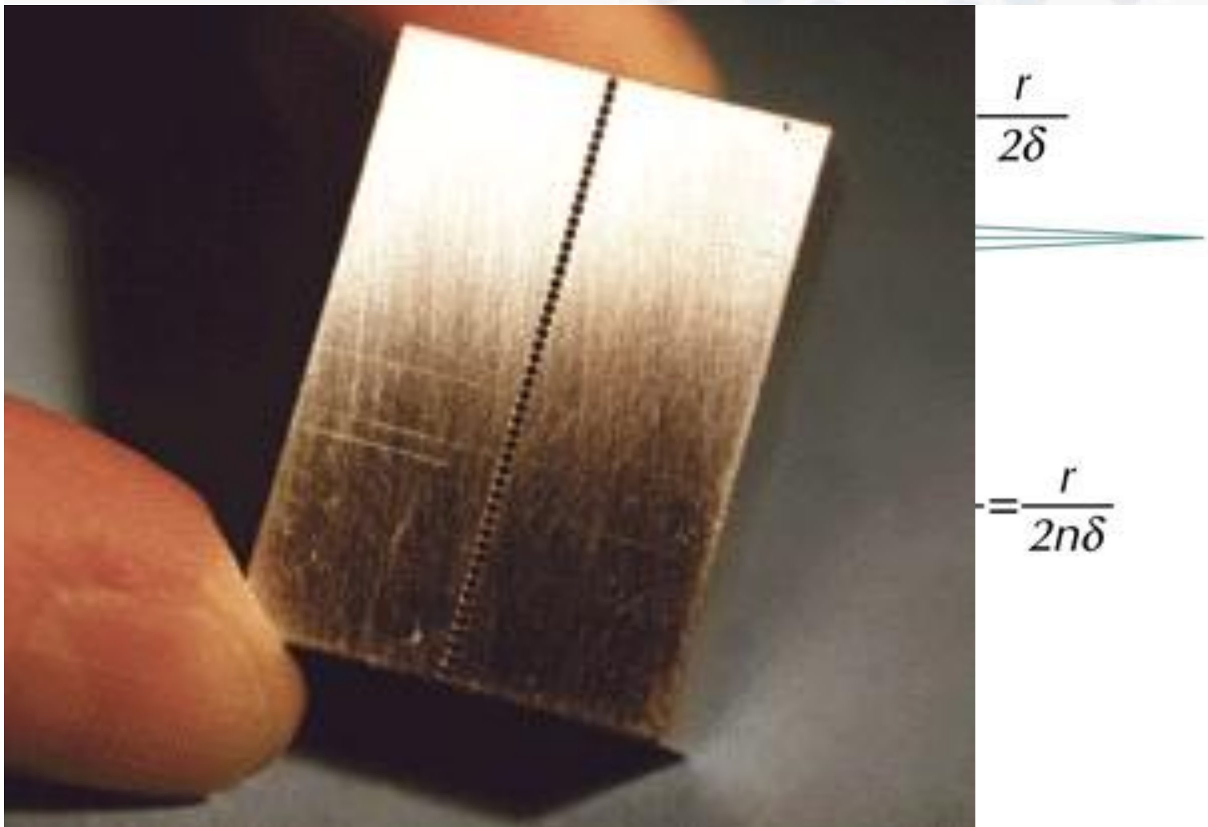


Refractive Lenses

"… The refractive index…. cannot be more than 1.05 at most….
….<u>X-rays cannot be concentrated by lenses</u>…"

W.C. Röntgen
Über eine neue art von Strahlen.
Phys.-Med. Ges., Würzburg, **137**, p. 41, (1895)
*English translation in Nature **53**, p. 274*

$n=1-\delta+i\beta$ with $\delta, \beta <<< 1$



Example

Aluminium

$\lambda=0.9$ A

$n=1-\delta_{Al}=1-2.8\,10^{-6}$

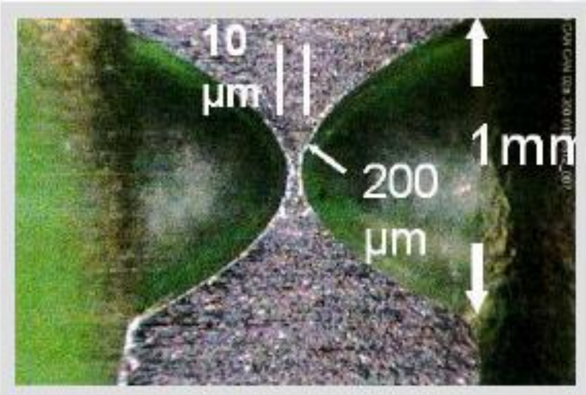
r= 300 μm 30 holes

$$F=\frac{r}{2\delta}=54\text{ m}$$

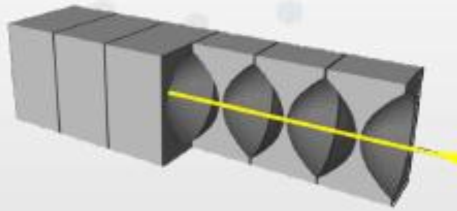
$$F=\frac{r}{2N\delta}=1.8\text{ m}$$

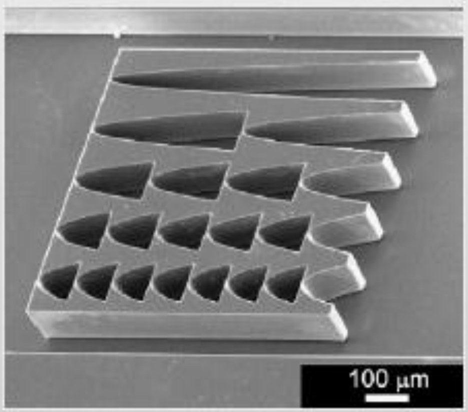
Snigirev et al. Nature 384, 49 - 51 (07 November 1996);

Parabolic Refractive lenses

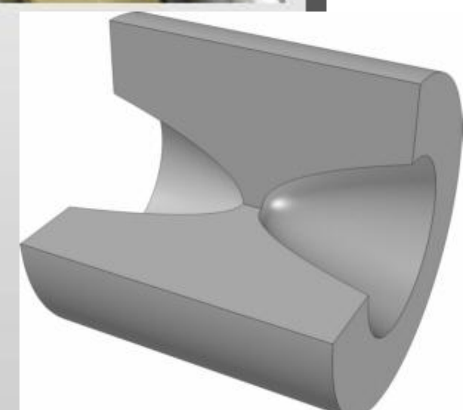


Materials:
low Z, high density
Al, Be, B, Si, ...



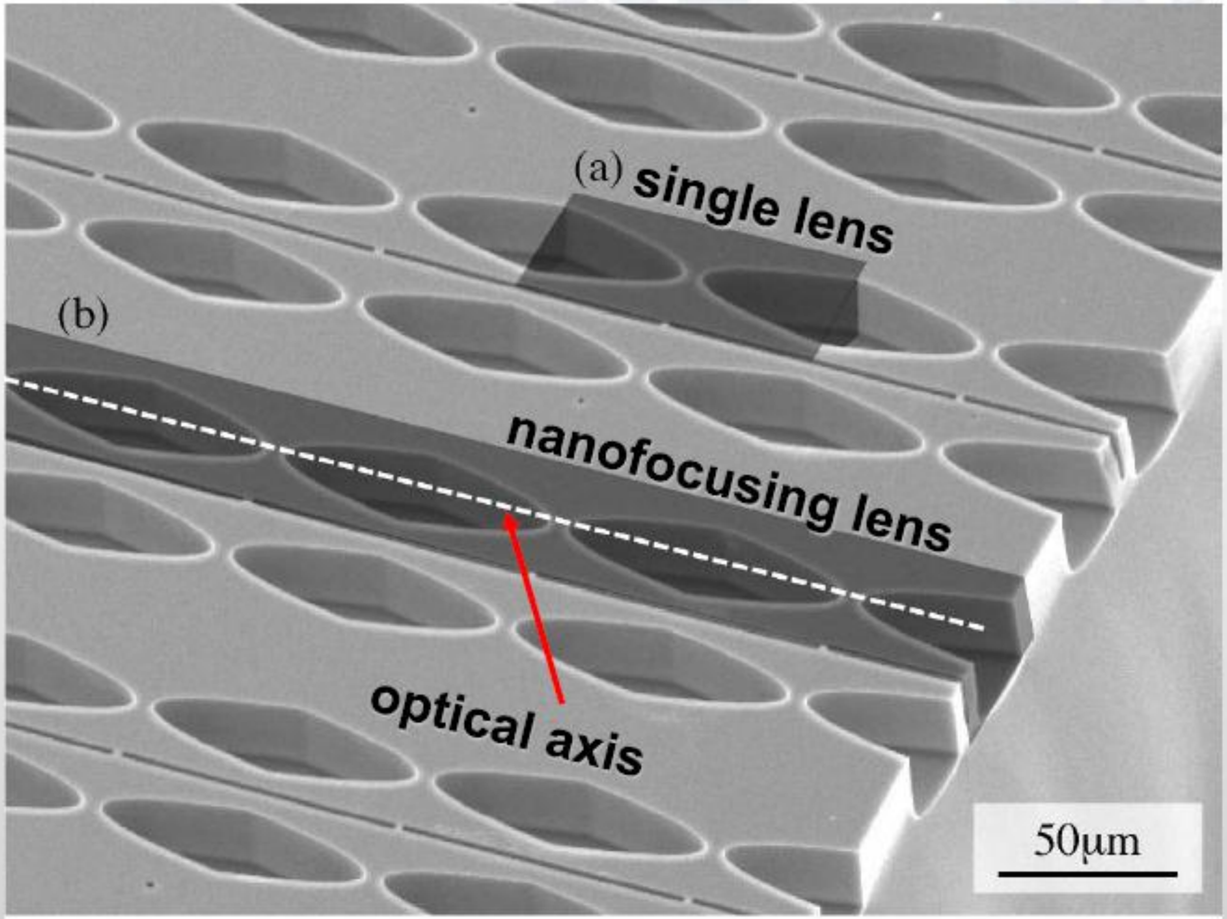


C. David et al.
PSI, Villigen, Switzerland



B. Lengeler, C. Schroer, M. Richwin,
RWTH, Aachen, Germany

Refractive Lenses



extreme curvature:

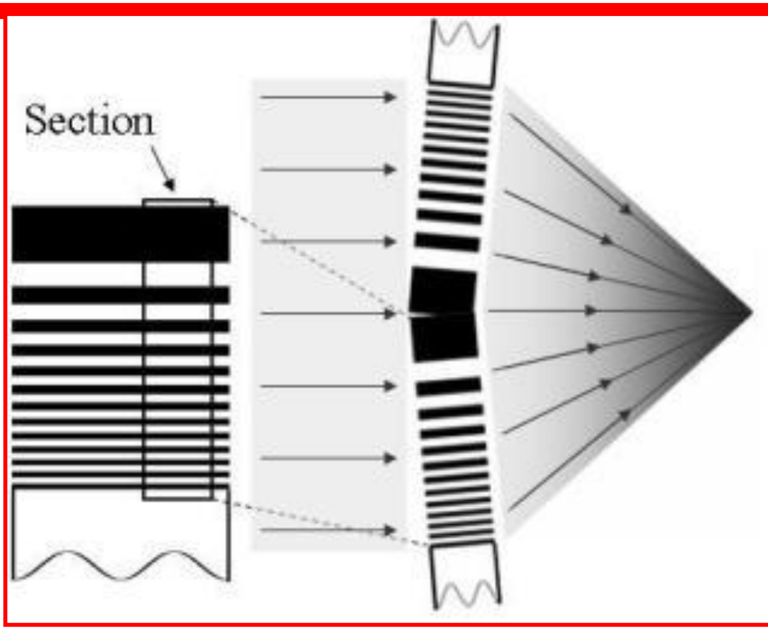
R = 1µm - 3µm

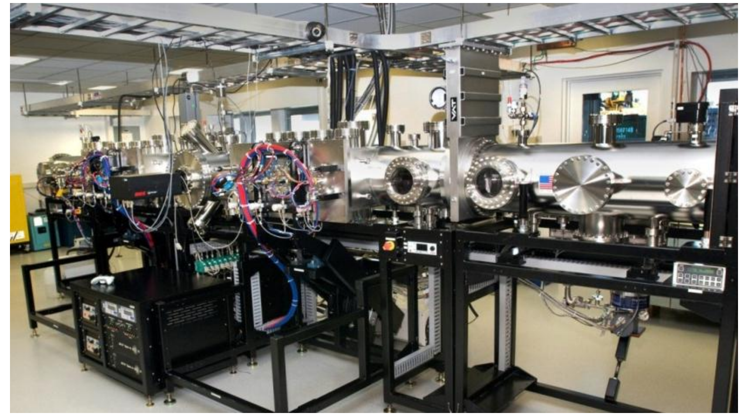
N = 50 - 100

lens made of Si by e-beam lithography and deep trench reactive ion etching

C. Schroer *et al*, *Applied Physics Letters*, 82(9), 2003

Nanofocusing Development





SEM of 1st MLL grown in new deposition system

- **MLL deposition laboratory established and in operations at BNL:**
- **Growth of MLLs: Mitigated interfacial stress build up using reactive gas mixture, and fabricated 68um-thick MLL thin-films**

(dr = 4 nm).

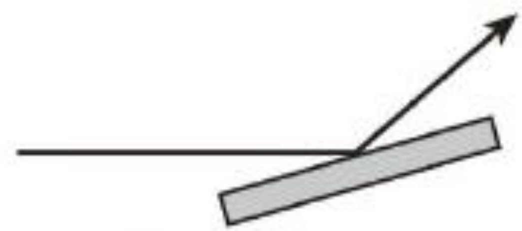
- **Used RIE/FIB to section MLL optics**
- **2D focusing using crossed MLL's achieved 25nm x 27nm (experiment conducted at APS 26-ID)**

Reflective Optics

Few reminders on reflective optics

Mirrors

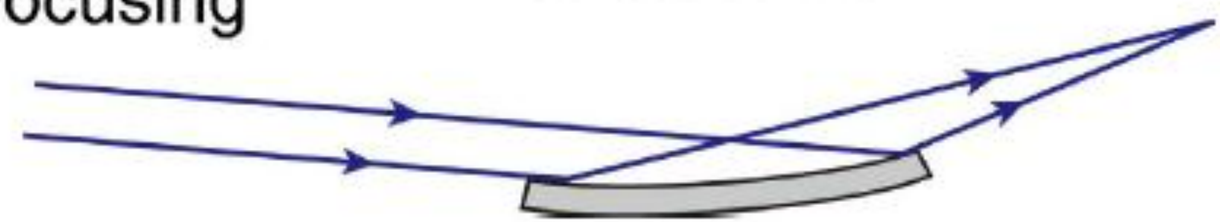
- Deflecting the beam



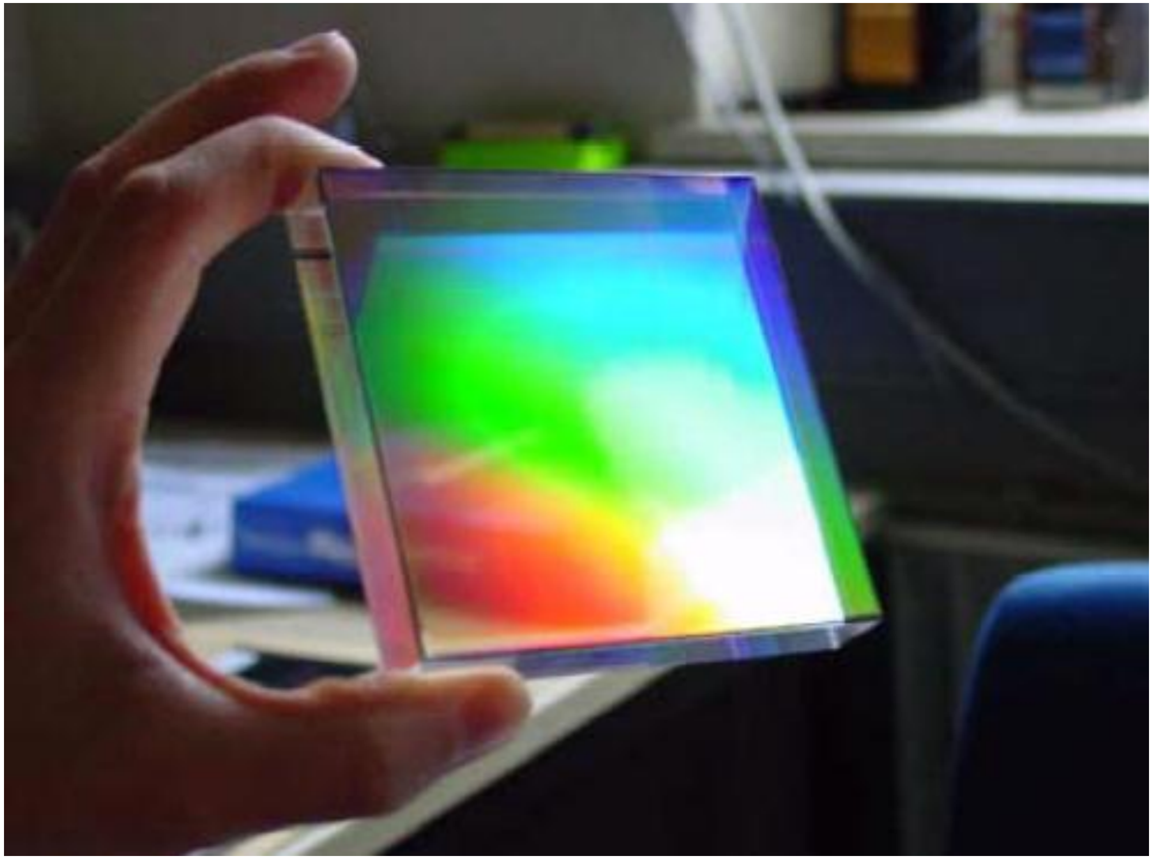
- Low pass filter

- Collimation

- Focusing



Diffraction grating



- Blazed or lamellar
- Low roughness < 0.3 nm rms
- Low slope errors < 100 nrad rms
- Mostly Silicon substrate
- Size around 200 mm max.

Need for Variable line spacing to Correct aberration

Main application : monochromator - spectrometer

X-ray Mirror : Overview

- Every new advance in SR source design has driven improvements in optical components to enable **smaller focal spots (Nanoprobe)**

- Chronology of SR mirror slope error specs:

(<1980) NSLS	2 arc sec (10µrad)	
1995	1 arc sec (5µrad) for 10µm spot	This was difficult for vendors to achieve
2006	0.2 arc sec (1 µrad) for 1µm spot	This is now "routine"
NOW NSLS II	**0.02 arc sec (100 nrad)**	Factor of 10 improvement required(!!!)

From Lord KELVIN

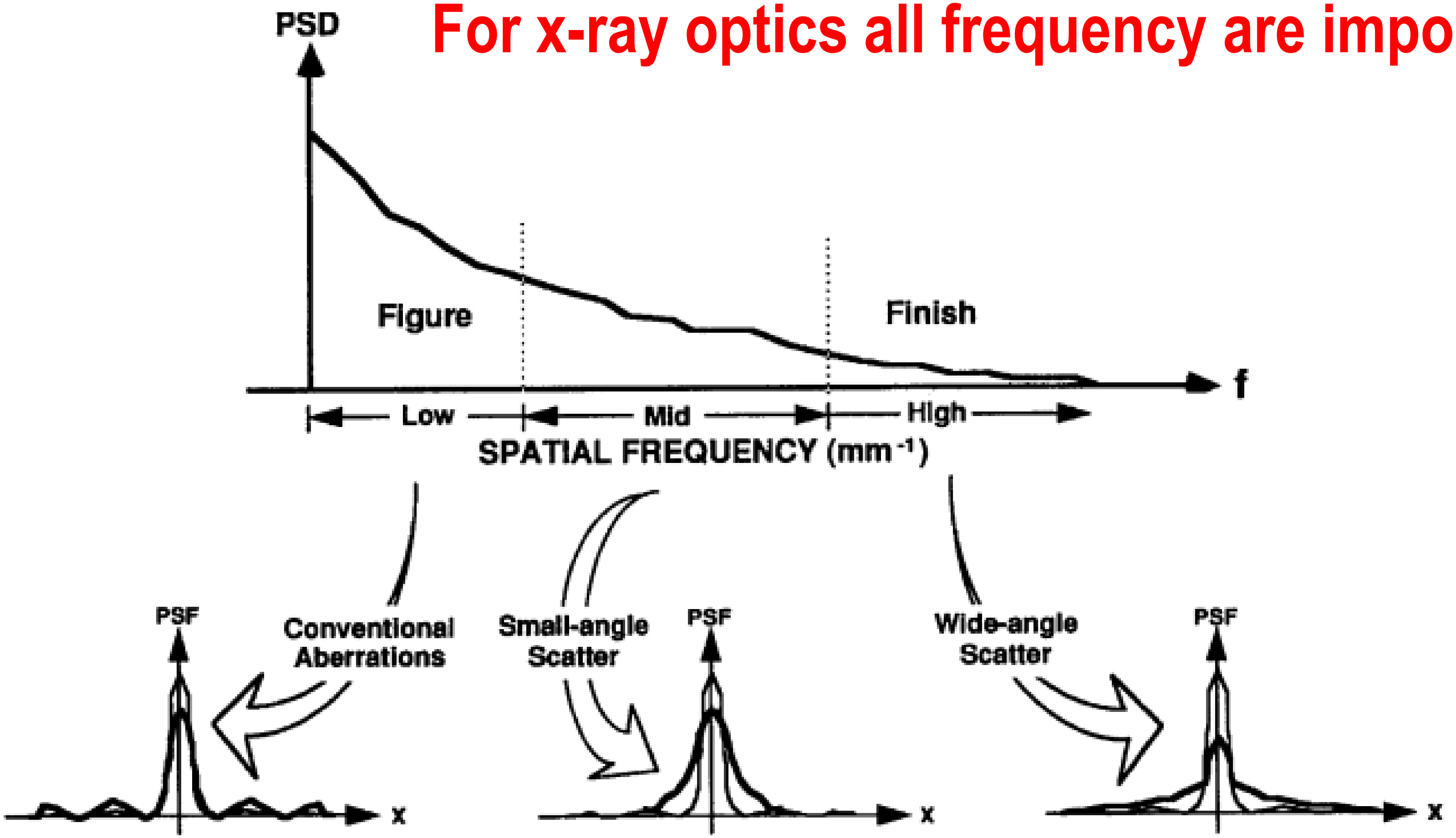
IF YOU CANNOT MEASURE IT YOU CANNOT IMPROVE IT

The key is the METROLOGY

Metrology requirements

Effect of the surface quality differs on each spatial frequency regime

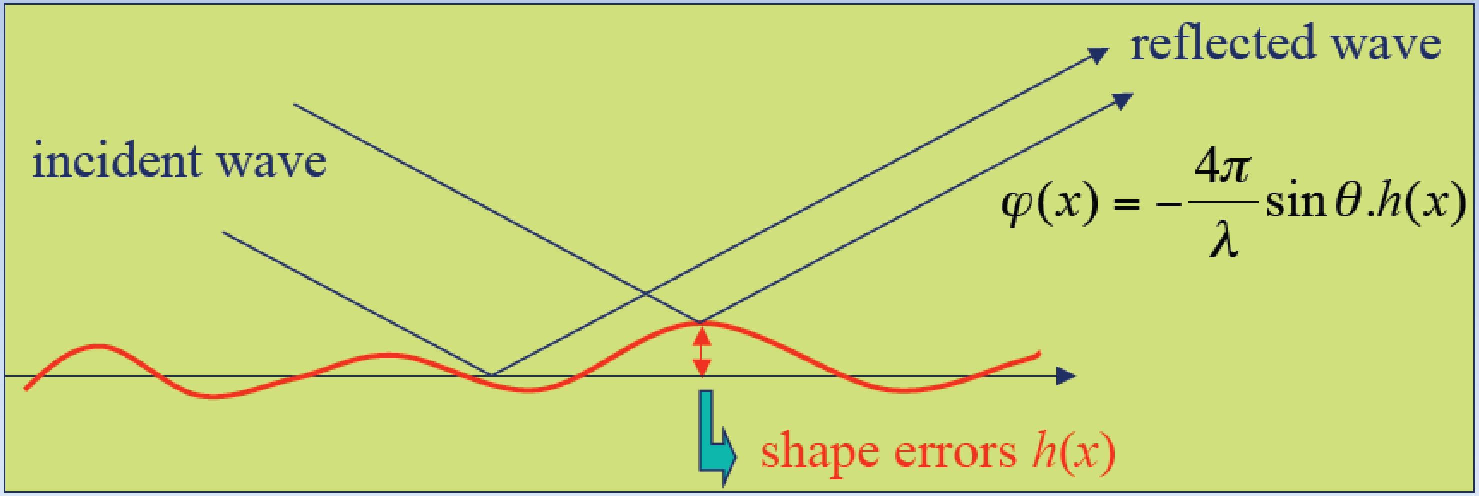
For x-ray optics all frequency are important



X-ray Optics New Challenge

Diffraction limited Optics at 0.1 nm wavelengt   What does it mean?

!! quality of the substrate !!



Wavefront error <λ/4 PV	⇒	Mirror Shape error <λ/8θ PV
Wavefront error <λ/14 rms		Mirror Shape error <λ/28.θ rms

At λ=0.1 nm (θ=3 mrad)

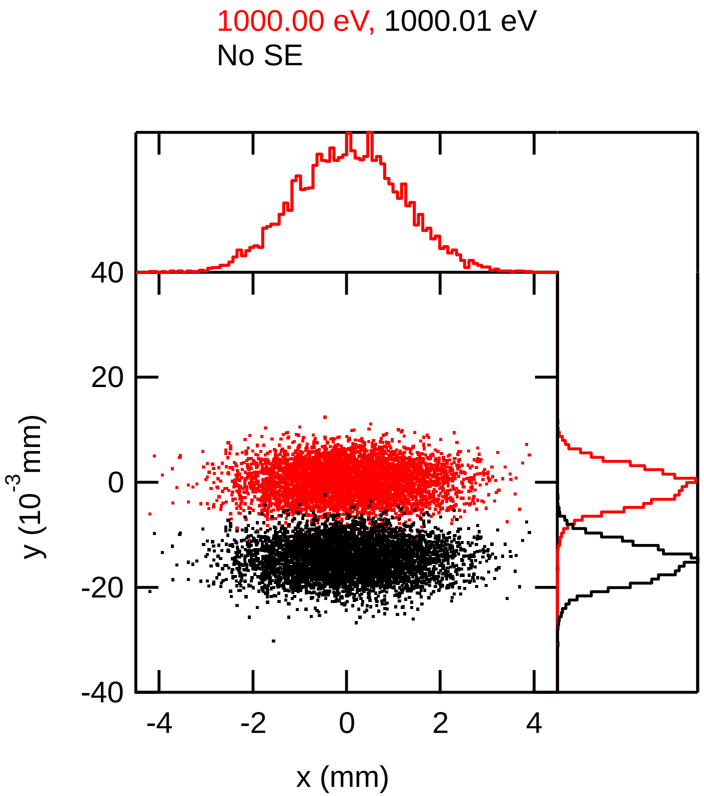
the shape errors need to be around 1 nm rms.

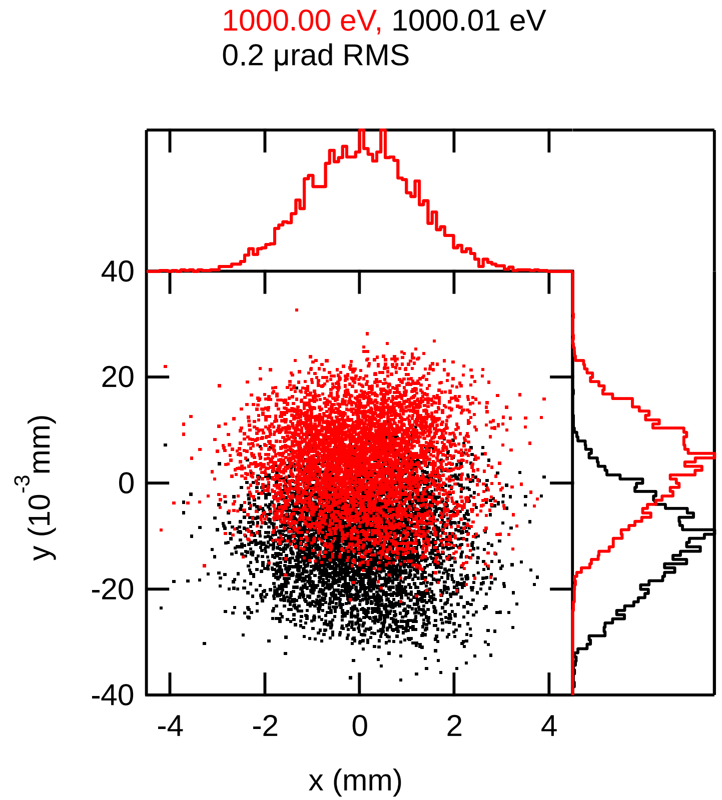
Slope errors effect : Grating example

Beamline monochromator: Plane mirror, plane VLS grating

From Ruben Reininger APS)

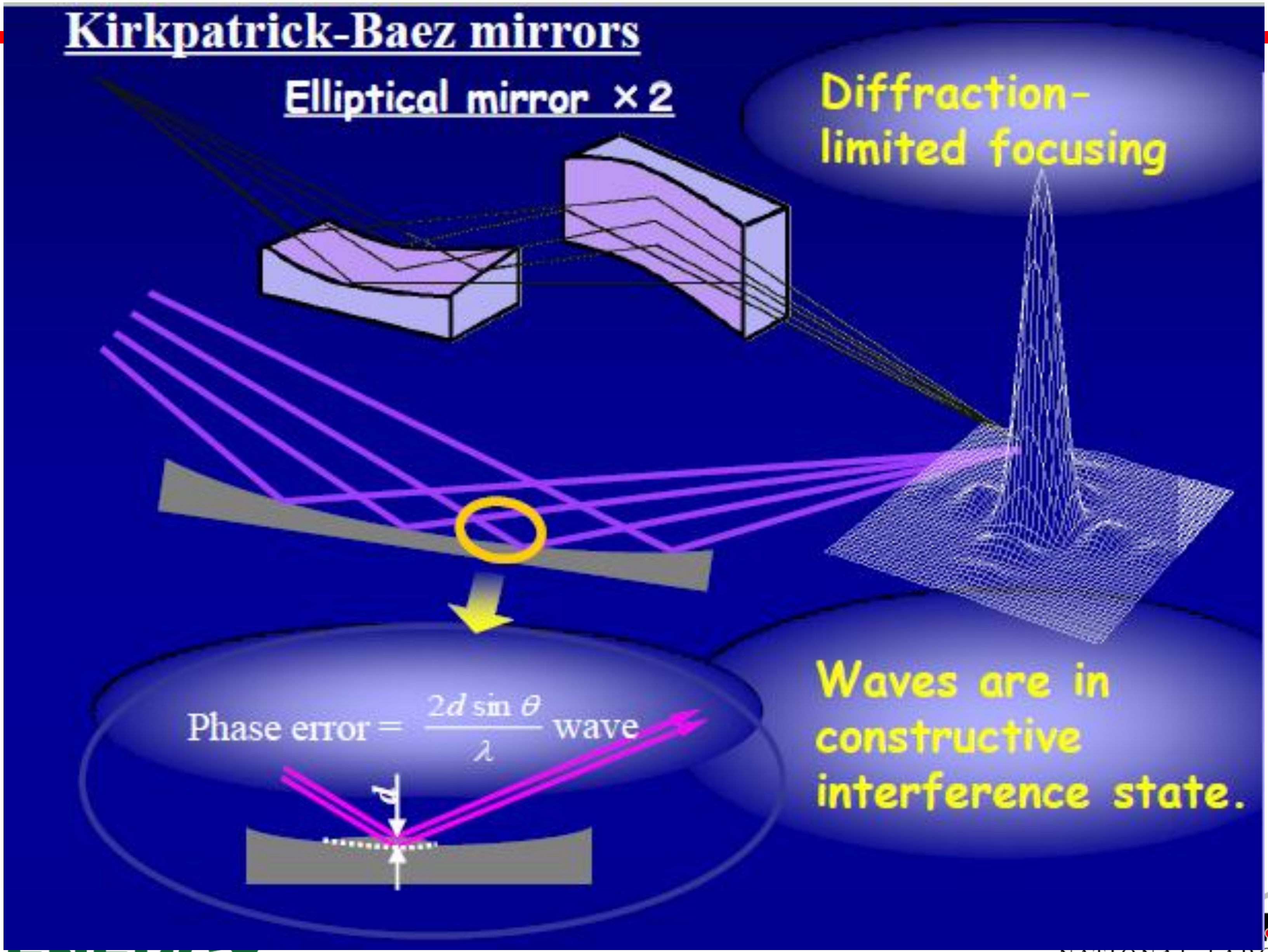
Source size = 18 µm VLS 1800 l/mm





Need better than 100 nrd rms slope errors (from 1 mm to the length of the grating)

X-ray Optics New Challenge



Elliptical Mirror Figuring

A light for Science

Two basic approaches:

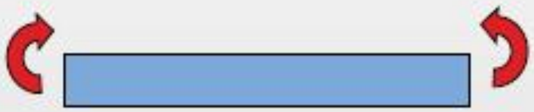
Static Figuring

- Elliptical figure polished into mirror substrate

- Relatively simple mechanics
- OK for very short radius ellipses
- Lengthy/expensive fabrication
- Only optimised for one set of operating conditions (incidence angle, focusing distance)

Dynamic Figuring

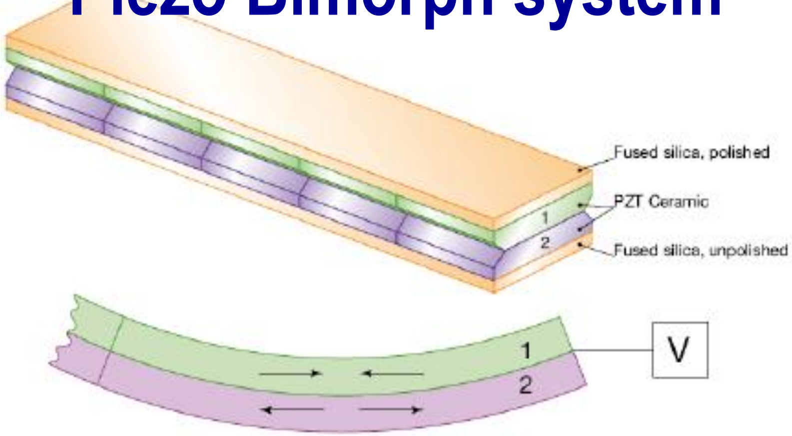
- Elliptical figure by mechanical bending of a (usually flat) mirror substrate



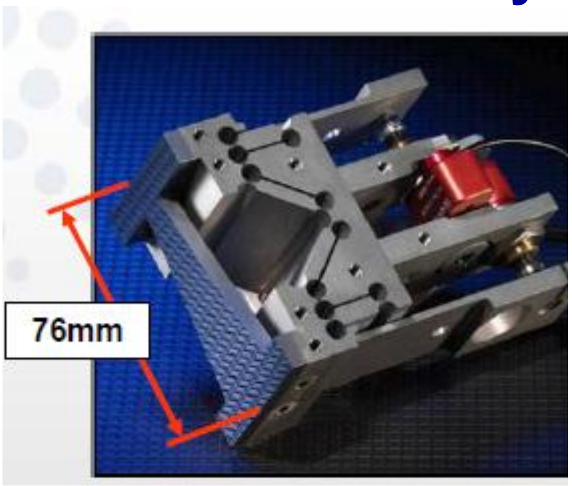
- Simple substrate polishing
- Relatively cheap systems
- Active systems allowing modification of focusing parameters (permits use at variable energy with Multilayer coatings)
- Not well adapted for very short radius ellipse (mirror will break!)

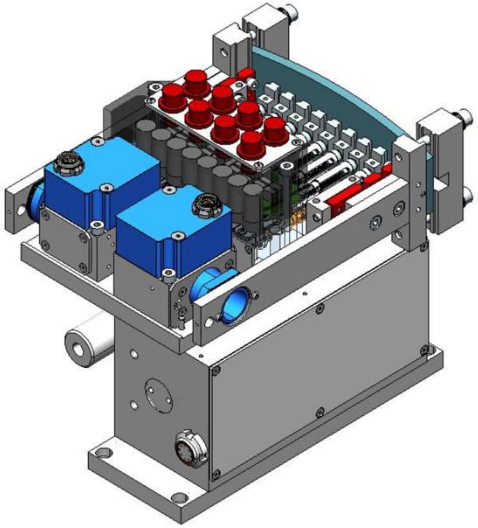
X-ray Active Optics : Family

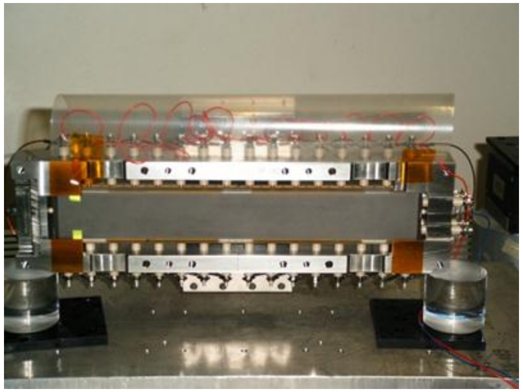
Piezo Bimorph system

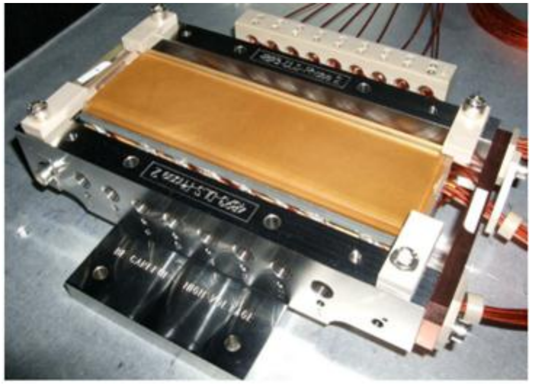


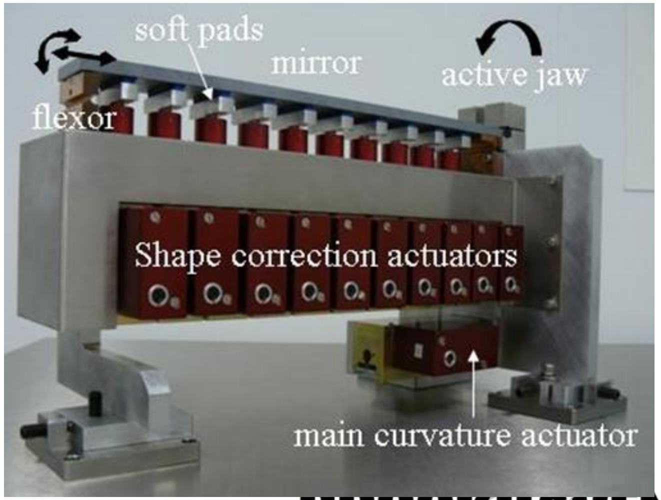
Mechanically actuated system



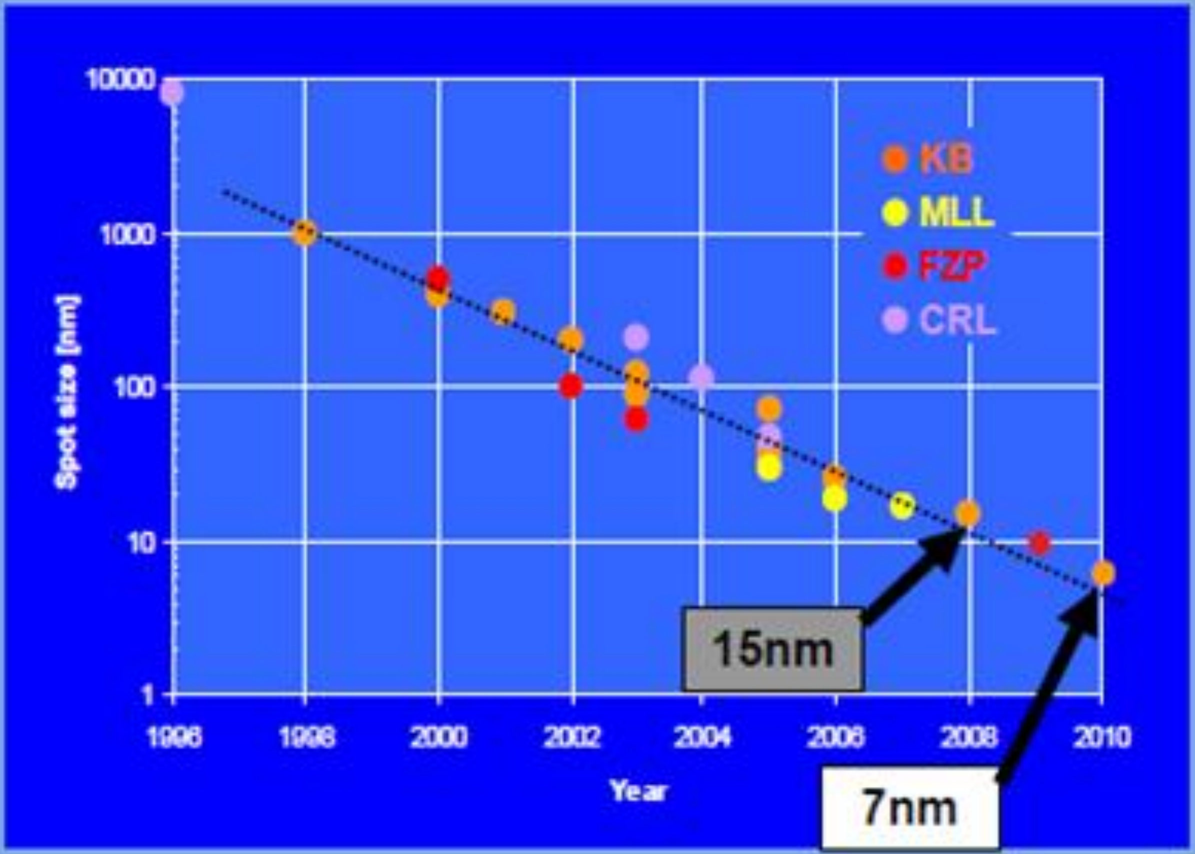






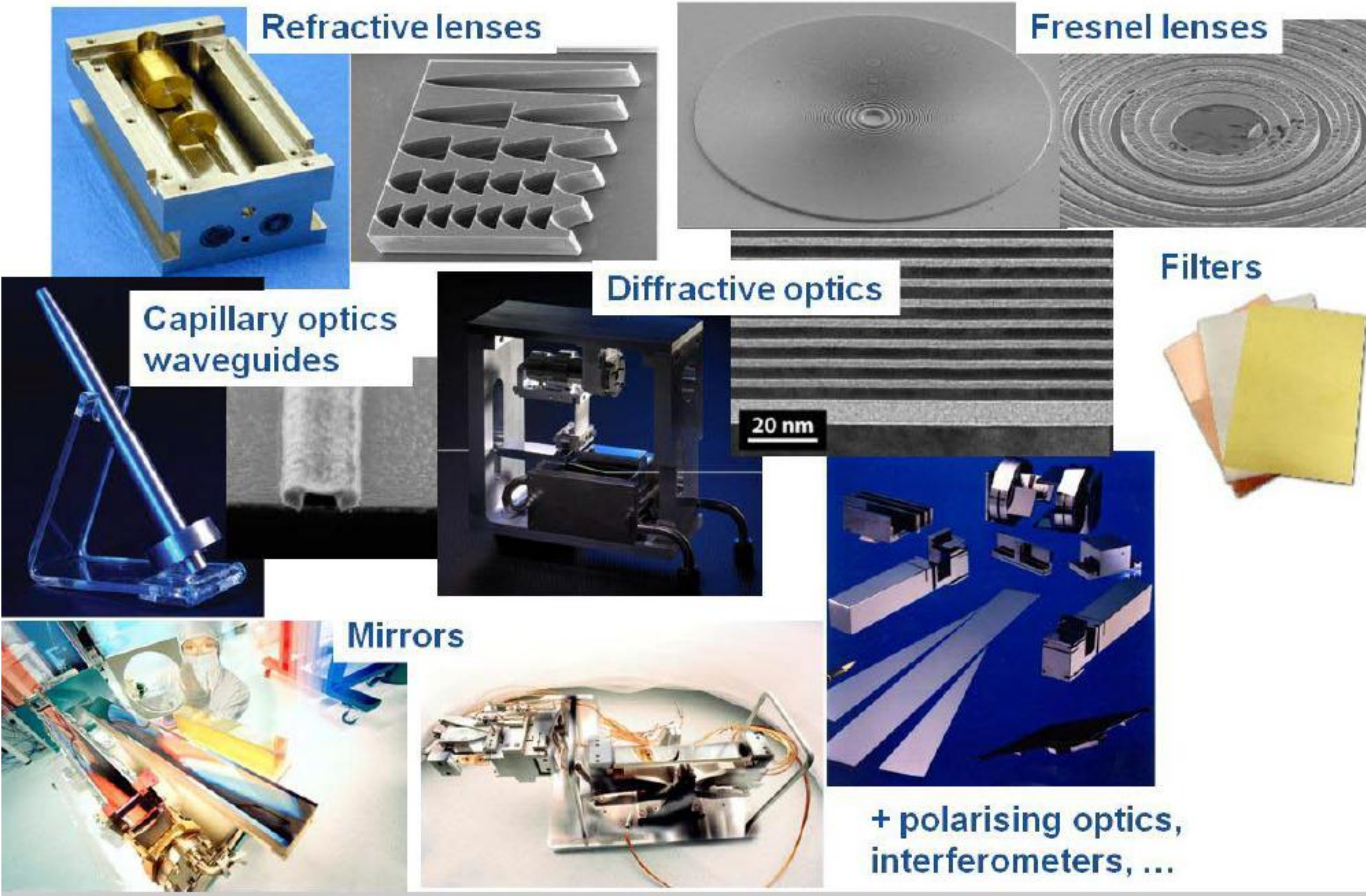


Moore's law adapted to x-ray optics focusing



Historical evolution of the measured spot size for different hard x-ray focusing elements *(courtesy C. Morawe)*

X-ray Optics



Refractive lenses

Fresnel lenses

Filters

Diffractive optics

Capillary optics
waveguides

Mirrors

+ polarising optics,
interferometers, ...

CONCLUSION

The advent of 3rd synchrotron and 4th generation FEL sources has encouraged the development of new x-ray Optics

- Drastic improvement in manufacturing and preparation techniques
  - Low roughness. High accuracy figuring, perfect crystal (Ge, Si Diamond)
- Improve power management strategies
- Focusing optics (spot size ~ few um to 10 nm or less)
  - Zone plate and refractive lenses, MLL, elliptically figured mirrors …

R&D programs continuously in progress : current "hot" topics

- Sub 10 nm focusing
  - Preservation of mirror wavefront quality optics
    - Mirror Polishing - Active optics → Ex and In Situ Metrology
  - Diffractive optics development : Grating – Zone Plate
  - Multilayers /Laue Lenses + Refractive lenses
- Simulation x-ray wavefront propagation
- Instrumentation : Heat load management – Ablation – Nanopositioning etc ..

Acknowledgments

Google for all the images I found on the web

Ray Barrett - Jean Susini ESRF

Ruben Reininger APS

CXRO - NSLS II

etc …

THANK YOU FOR YOUR ATTENTION